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13. ABSTRACT *(Maximum 200 words)* The MODIS BRDF/Albedo Product will provide multi-band BRDF parameters and albedo measures at 1 km resolution globally every 16 days, utilizing both MODIS and MISR data. The BRDF models to be used are kernal-driven semi-empirical models based mostly on Ross and Li-kernels. These are capable of fitting directional data observed for different land cover types by Kimes as well.

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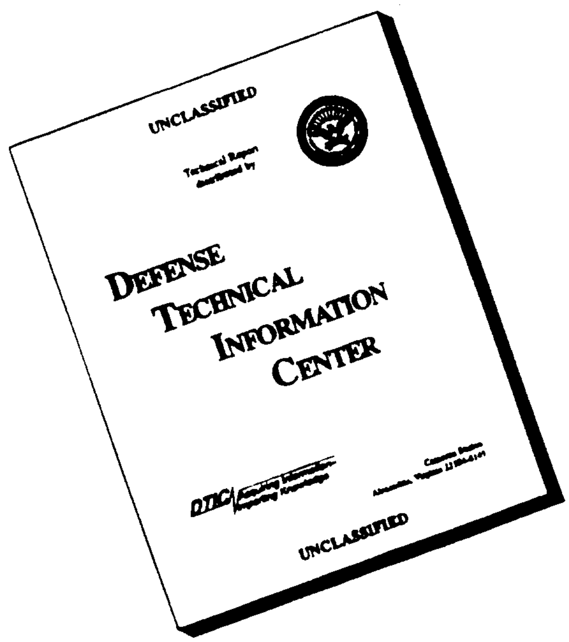

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Global Mapping of Bidirectional Reflectance and Albedo for the EOS MODIS Project: The Algorithm and the Product

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Abstract – The MODIS BRDF/Albedo Product will provide multi-band BRDF parameters and albedo measures at 1 km resolution globally every 16 days, utilizing both MODIS and MISR data. The BRDF models to be used are kernel-driven semiempirical models based mostly on Ross and Li-kernels. They are capable of fitting directional data observed for different land cover types by Kimes well.

Introduction

The EOS-AM-1 platform, to be launched in 1998 carrying several instruments, will provide a key component of NASA's Earth Observing System (EOS) to the regional, mesoscale and global climate and climate change and the earth system science communities. Among the instruments is MODIS, the Moderate Resolution Imaging Spectroradiometer, which will be employed to deliver not only a series of remotely sensed products related to the oceans and the atmosphere, but also a group of global products focusing on the land surface of the earth. These land products are particularly important since the land surface, especially if it is vegetated or displays varied topography, is part of the influential lower boundary of the earth's climate system.

One of the land products is the MODIS BRDF/Albedo Product (P.I.: A. H. Strahler and J.-P. Muller), which is important in several respects: it allows correction of images for directional effects; standardizing images to common viewing and illumination geometries; it provides lower boundaries for atmospheric correction and for radiation budget investigations; allows retrieving precise measures of land surface albedo; inferring land surface structural characteristics, especially of vegetation and topography; and is an input to land cover classification.

BRDF

The brightness of a scene (pixel) depends both on the angle at which it is viewed and at which it is illuminated; this dependence is described by the bidirectional reflectance distribution function (BRDF), and is due to shadows in a scene hiding or emerging as viewing and/or illumination angles change, and due to the intrinsic directionality of the reflectance of the constituents of a scene, for example the leaves of plants. Since the MODIS sensor is designed to achieve a high repeat-rate in observing a point on the ground by viewing the earth's surface at cross-track angles of up to $\pm 55°$, knowledge of the BRDF is required for intercomparisons of pixels across images and for extrapolating reflectances to nadir-equivalent values, needed, e.g., for improved calculations of the NDVI. The MODIS BRDF/Albedo Product will provide the BRDF function in form of the parameters of a BRDF model, which may then be used to interpret surface reflectivity and structure. Directional information is also relevant for all calculations tracing the passage of the remotely sensed signal through the atmosphere. Availability of the BRDF/Albedo Product will increase the accuracy of atmospheric correction and radiation budget schemes applied to the data by several percent [1].

Albedo

There are two possible approaches to modeling surface reflectivity. One is to describe the directionality of surface-leaving radiance under the atmospheric conditions prevailing during the observations. Diffuse illumination, a consequence of the aerosol load of the atmosphere, is taken into account in deriving the directional characteristics of the scattering occuring. The integral of this reflectance distribution function is the albedo of the pixel, as observed. While this approach gives a precise characterization of the radiative state of the surface at the time of the observation, the results obtained are not directly applicable to other times of the day, when diffuse and direct contributions to illumination have changed, or to other days, when the aerosol optical thickness may be different.

The second approach models radiation scattering as a property of the surface alone, requiring as input data that were precicely corrected for atmospheric effects. The BRDF is given for the idealized case of delta-function-like illumination, i.e., absence of an atmosphere. The directional-hemispherical integral of the BRDF, which we here term "black-sky albedo', is then the albedo of the

pixel assuming a perfectly clear atmosphere. The bihemispherical integral, termed "white-sky albedo", is the albedo of the scene under perfectly diffuse illumination. The actual albedo at a given point is then a value in between the black-sky and the white-sky albedo, the point of interpolation depending on the prevailing aerosol optical thickness at the time of interest. The BRDF data and its integrals, however, are themselves independent of the time considered and of atmospheric state.

While the MISR surface product will provide a useful measure of the first type, the MODIS BRDF/Albedo Product will combine MODIS and MISR data over a period of time to derive a product of the second type based on more complex models of the BRDF of various types of land cover. Both black-sky albedo, as a function of solar zenith angle, and white-sky albedo will be derived to provide surface reflectance measures that are independent of the time of observation.

Models to be used for BRDF inversion

The models currently most suitable for global BRDF modeling at the kilometer scale are of the linear semiempirical type. These combine some of the advantages of simple empirical models with the advantages of complex physical models while avoiding the respective disadvantages. While physical models usually assume homogeneity of a scene, are costly to calculate and need to be inverted numerically, semiempirical models are less complex, accomodate to some extent mixed-pixel situations, and may be inverted analytically through matrix inversion if they are of the kernel-driven type explained below. Nevertheless, they retain some of the physical basis of the BRDF shape, having been derived from approximations to full physical models. This allows confident extrapolation of the BRDF from angular ranges where observations were acquired to other angle ranges. With the MODIS and MISR sensor combination, for example, only a limited range of solar zenith angles will occur in each observation as a function of time of year and the location of the point considered on the ground. For albedo computations and standardization purposes, however, the BRDF is also needed at other solar zenith angles. The extrapolations needed are greatly facilitated if the BRDF model used describes the scattering process as a physical process. Empirical models of the BRDF do,'t do that; they may fit observations well but are likely to be more problematic in the angular extrapolation of the BRDF unless a good coverge is provided in both vieweing and illumination hemispheres. Last but not least, the parameters found from inversion of semiempirical models may still be related roughly to land surface physical properties, while the parameters of empirical models are not directly interpretable in such a way. As a consequence, unconstrained use of the BRDF for standardization of reflectances and inference of surface properties from the angular signature while at the same time keeping the computer processing requirements at a realistic level can currently be best achieved by employing kernel-driven semiempirical BRDF models. This is the approach taken by the MODIS BRDF/Albedo Product.

The BRDF of different land cover types varies greatly. As a consequence, no single BRDF model is equally suitable for all land cover types. The MODIS BRDF/Albedo algorithm will select from a suite of models, each appropriate for a specific radiation scattering situation, the one that fits the observations best, adjusting the model parameters in the process so as to achieve the best result. Three basic types of scattering may be distinguished: isotropic Lambertian scattering; volume scattering as from horizontally layered vegetation such as crops; and surface scattering as from vegetation canopies with distinct crowns such as sparse forests, or varied topography. Even for homogeneous pixels a mix of these types is to be expected, and in mixed pixels the different types of scattering will be related to the areal proportion of the types of surfaces present. Consequently, following an approach by Roujean, Leroy and Deschamps [2], the BRDF is modeled as a linear superposition of these basic types of scattering,

$$R(\theta_i, \theta_v, \phi) = f_i + f_v k_v(\theta_i, \theta_v, \phi) + f_s k_s(\theta_i, \theta_v, \phi),$$

where R is the reflectance, k_v and k_s are functions depending only on geometry, where k_v describes volume scattering and k_s surface scattering, f are the weights of these functions in the superposition, θ_i and θ_v are illumination and viewing zenith, and ϕ the relative azimuth. The function k are referred to as "kernels", and a model of this type may be referred to as a kernel-driven model [4]. Each kernel is derived from a physical theory of radiation scattering of the land surface. The volume-scattering kernels are derived from theories of radiative transfer, the surface-scattering kernels from geometric-optical theories. The parameters of the BRDF model, f, may be expressed in terms of physical properties of the scene such as leaf area index, shape and height of trees, surface reflectance etc.; in inversion the three quantities f are retrieved, providing the relative influence of the respective type of scattering on the directional signal observed.

The kernels that will be used in the MODIS BRDF/Albedo algorithm are the following. For k_v, two types of Ross-kernels are available. One is an approximation to the radiative transfer theory of Ross [3] for large values of the leaf area index ("thick" approximation) [2], the other for small values ("thin" approximation) [4]. For k_s, three types of kernels are available. One is the Roujean geometric-optical kernel [2], and two are Li-kernels derived from the full geometric-optical mutual shadowing BRDF model for forest canopies by Li and Strahler [5]. The first of these is an approximation for a sparse ensemble of discrete objects (crowns) [4,6], the second for a dense ensemble, including treatment of mutual shadowing [4,6]. The Li-kernels furthermore come in 4 types each, distinguished by describing prolate or slightly oblate and objects positioned low or high above the ground. An additional volume-scattering kernel for scenes involving snow is being prepared. All in all, 20 BRDF models may be formulated in this way. Tests have shown that for each spe-

cific land cover type at least one of these models performs better than the others, even though for other land cover types the models may do equally well. A crop canopy, for instance, will typically lead to a small value of the geometric-optical parameter f_s, making it mostly irrelevant which surface-scattering kernel is chosen in the modeling. However, surface-scattering land cover types require that the distinction between these kernels be retained, and vice versa.

The algorithm

MODIS level-2 reflectances that have been atmospherically corrected are binned into the MODIS level-3 grid over a period of 16 days and combined with all MISR observations acquired in the same period. Depending on the time of the year and latitude, between 30 and 60 looks will be typically acquired during that period, but cloud cover will reduce this number to various extents [1]. The directional observations thus assembled are then analyzed by inverting the suite of above-mentioned models to find the one that describes the observations best.

The MODIS BRDF/Albedo product will be provided in 7 MODIS land bands, centered at 0.470, 0.555, 0.659, 0.865, 1.240, 1.640, and 2.130 μm; the four MISR bands correspond closely to four of the MODIS bands. Spatial resolution will be 1 km, temporal resolution 16 days.

The atmospheric correction algorithm will interact with the BRDF algorithm as follows. First, atmospheric correction will be conducted assuming a Lambertian surface, and the resulting reflectances are used to infer a BRDF. This in turn is used to improve the atmospheric correction, after which the BRDF is re-derived. It has been shown [1] that this procedure increases the accuracy of the derived reflectances, the parameters of the BRDF model and the albedo found typically by several percent, in turbid conditions by more than 10 percent.

BRDF model inversion is carried out by matrix inversion [7]. The production algorithm has been programmed to provide maximum efficiency through avoiding multiple evaluation of expressions shared by several kernels, and through look-up table approaches to kernel value retrieval and albedo calculations (note that the parameters of a kernel-driven model are also the weights of the respective integrals of the kernels in albedo calculation, which may be pre-computed).

The MODIS BRDF/Albedo Product will provide as a measure of the BRDF found an identifier of the best-fitting model, and the corresponding parameters in each band. A user working with the product will need to reconstruct the BRDF using an algorithm that allows forward modeling of each of the models used in the inversion. Such a code is available to users in form of "Ambrals" (Algorithm for MODIS bidirectional reflectance anisotropies of the land surface), a code that allows forward and inverse BRDF modeling of kernel-driven models, provides a selection of science options, numerical BRDF integration, and easy adding of new models. The Ambrals code, together with a user guide, may be obtained from the authors via ftp upon request for BRDF modeling work and preparation of BRDF-dependent algorithms.

Details about the algorithm, its theoretical basis, its dependence on other products, and on the output format may be found in the corresponding NASA Algorithm Technical Basis Document [1].

Output product, quality flags

Full results will be recorded for the model found to have the lowest average RMSE over bands, where the error is relative error. The parameters of that model are given as well as white-sky albedo and the coefficients of a polynomial describing the solar zenith angle dependence of black-sky albedo. All of these are given in the seven MODIS land bands. Albedos are also given for the shorter ($< 0.7\mu$m) and the longer ($> 0.7\mu$m) end of the spectrum as well as for the whole spectral range.

Furthermore, a number of quality and consistency flags are given. These indicate angular range and coverage of the observations, goodness of the fit over bands, consistency of the model choice and of the parameters found (where seasonal trends will be taken into account). Overall quality and consistency determinators will allow users to choose the level of confidence they want data to possess for subsequent processing.

If a BRDF cannot be determined in a particular cycle, for example due to cloud cover, an older BRDF will be filled in to provide a complete BRDF database. These fill-ins will be either the last available BRDF for that pixel or, if seasonal trends play a role, the best estimate based on the previous experience with that pixel.

A subset of information will also be recorded for a second and a third BRDF model. This subset will only include the model parameters; but note that albedo can readily be retrieved from these parameters if needed. The second model will be a model that may not have the best RMSE, but is relevant for other reasons, either because land cover knowledge provides additional insight into the BRDF type to be expected or because that particular model was chosen most consistently in the past for that scene. The second model is intended to reflect the best knowledge of the BRDF of a pixel. The third model will be a modified version of the empirical modfied Walthall model [8]. This will allow researchers to plot global BRDF based on only one model, but RMSEs will mostly be higher in that case. Lastly, the RMSEs of all other models are recorded. The reason is that the pattern of how good or how bad the various models fit a given observation may is useful information for land cover classification. Not only the fact that a particular model fits an observation well is a significant piece of information, but also that another one doesn't.

Validation, Relationship to Land Cover

Validation of the BRDF/Albedo product needs to be per-

formed in two respects. First, the semiempirical BRDF models need to be validated for as many types of land cover as possible to assure that they provide adequate mathematical descriptions of occuring BRDF shapes. Secondly, large-scale BRDF and albedo retrieval need to be demonstrated given the constraints of sampling, atmospheric correction and temporal composition of data occurring in a remote sensing situation.

An indication of how well the new models perform for a variety of land cover types is given in Figure 1, where 6 of the 11 BRDF data sets for different land cover types assembled by Kimes and co-workers [9,10,11] have been inverted for each of the models available. The plot shows the average RMSE of the red and of the NIR band as a function of model type. A relative measure of error was used, but the result does not depend overly on the precise form of the error function. The data cover the whole viewing hemisphere at several different sun angles.

First, five of the six classes shown here are fitted well by at least one of the models. Only orchard grass is not well represented by any of the models. The results for the 5 other land cover types not shown here are similar. Second, the last 2 data points in each plot mark models that have previously been known and used (Ross-thick and Roujean-kernels; modified Walthall model). As can be seen, the new models making use of the Li-kernels are better than these in most cases due to the fact that they were derived from an extensive geometric-optical theory. Most strikingly, the hardwood forest class is fitted well now, which was the most problematic case in the pioneering investigations of Roujean et al. [2].

Third, different types of land cover lead to selection of specific types of kernel combinations. The hardwood forest type distinctly prefers the Li-dense kernel over Li-sparse. The forest observed by Kimes indeed had a coverage of over 90 percent. The fact that choice of Ross-thin or Ross-thick for the volume scattering kernel does not play a big role is due to the fact that the corresponding weight f_v is very small in a scene dominated by surface scattering so that details are not relevant. For the plowed field, slightly oblate forms are clearly preferred over prolate forms, in accordance with the rough surface of such a field presenting roundish clods. In orchard grass a preferance for a high value of the leaf area index is evident, and the sparse kernels are selected over the dense kernels. The latter is also true for the grassland. Wheat is dominated by radiative transfer-type scattering and thus only small variations with the type of geometric-optical kernel are to be seen; most models fit very well. For soybeans, the new geometric optical kernels improve the RMSE.

With respect to land cover classification, the most intersting aspect of these findings is the clear distinction in the response of BRDFs from discrete-object scenes as opposed to those from horizontally layered canopies. This may help separate, e.g., sparse woodland from dense brush, two classes that are difficult to separate on a spectral basis alone due to their comparable biomass.

Work currently under way or planned for the near future includes applying the MODIS BRDF/Albedo algorithm to AVHRR and ASAS scenes, investigating the influence of noise, systematic bias and sampling patterns on BRDF and albedo retrieval, and further developing the algorithm, especially with respect to rules for providing a best-estimate BRDF in parallel to the most recent actual BRDF measurement.

In summary, the MODIS BRDF/Albedo product will be a global product at 1-km spatial resolution allowing from mid-1998 on a continuous assessment of the reflective properties of the earth's land surface, intended for use in the civilian environmental and earth system research community.

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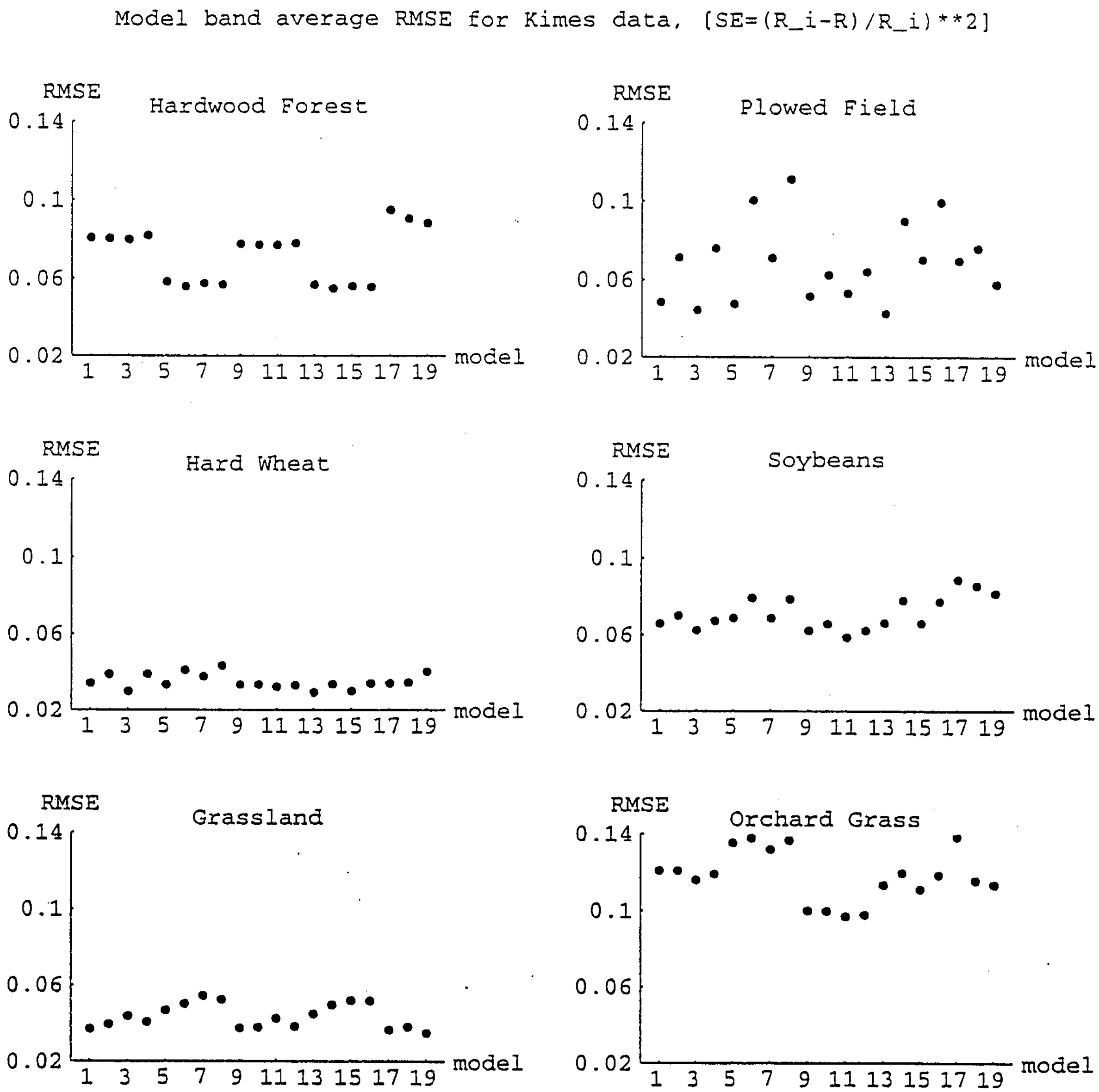

Figure 1: Band average RMSE for 6 selected land cover types (2 surface scattering types, 2 crops, 2 grasses (9,10,11]) as a function of model used in the inversion. The kernels used in the models are: models 1–8 and 17: Ross-thin, models 8–16 and 18: Ross-thick, models 1–4 and 8–12: Li-sparse, models 5–8 and 13–16 Li-dense, models 17 and 18: Roujean, model 19: modified Walthall; within each Li-sparse and Li-dense category the series is low-oblate, low-prolate, high-oblate, high-prolate.